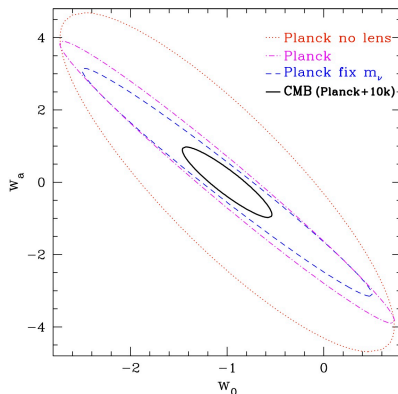


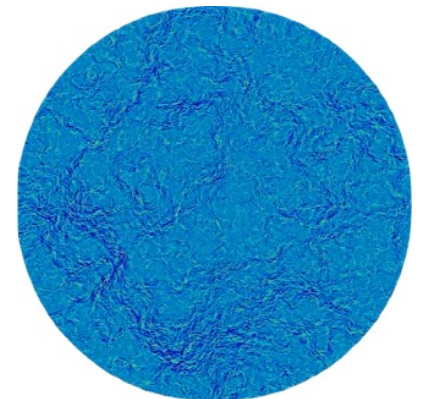
By Dawn's Early Light: CMB Polarization Impact on Cosmological Constraints

Eric Linder

Santa Fe Cosmology Workshop
16 July 2012



UC Berkeley & Berkeley Lab
Institute for the Early Universe, Korea

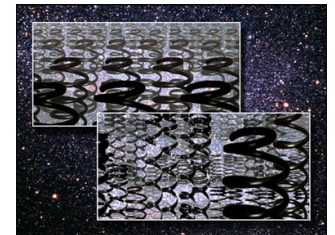


Nature of Dark Energy

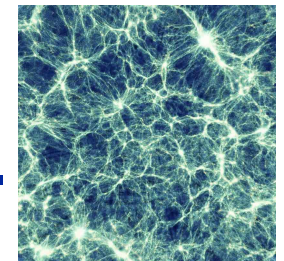


Dark energy is very much *not* the search for one number, “ w ”.

Dynamics: Theories other than Λ give time variation $w(z)$. Form $w(z)=w_0+w_a z/(1+z)$ accurate to 0.1% in observable.



Degrees of freedom: Quintessence determines sound speed $c_s^2=1$. Barotropic DE has $c_s^2(w)$. But generally have $w(z)$, $c_s^2(z)$. Is DE cold ($c_s^2 \ll 1$)? Cold DE enhances perturbations.



Persistence: Is there early DE (at $z \gg 1$)? $\Omega_\Lambda(z_{\text{CMB}}) \sim 10^{-9}$ but observations allow 10^{-2} .

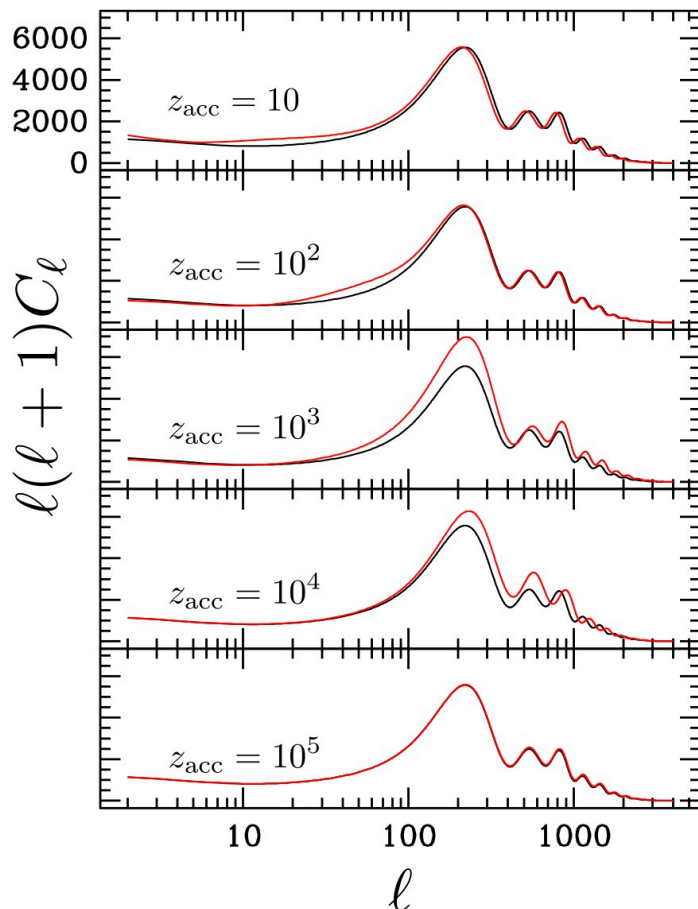


CMB Probes of Acceleration



How well do we really know the standard picture of radiation domination \rightarrow matter domination \rightarrow dark energy domination?

Maybe acceleration is occasional. (Solve coincidence)



Effect of 0.1 e-fold of acceleration

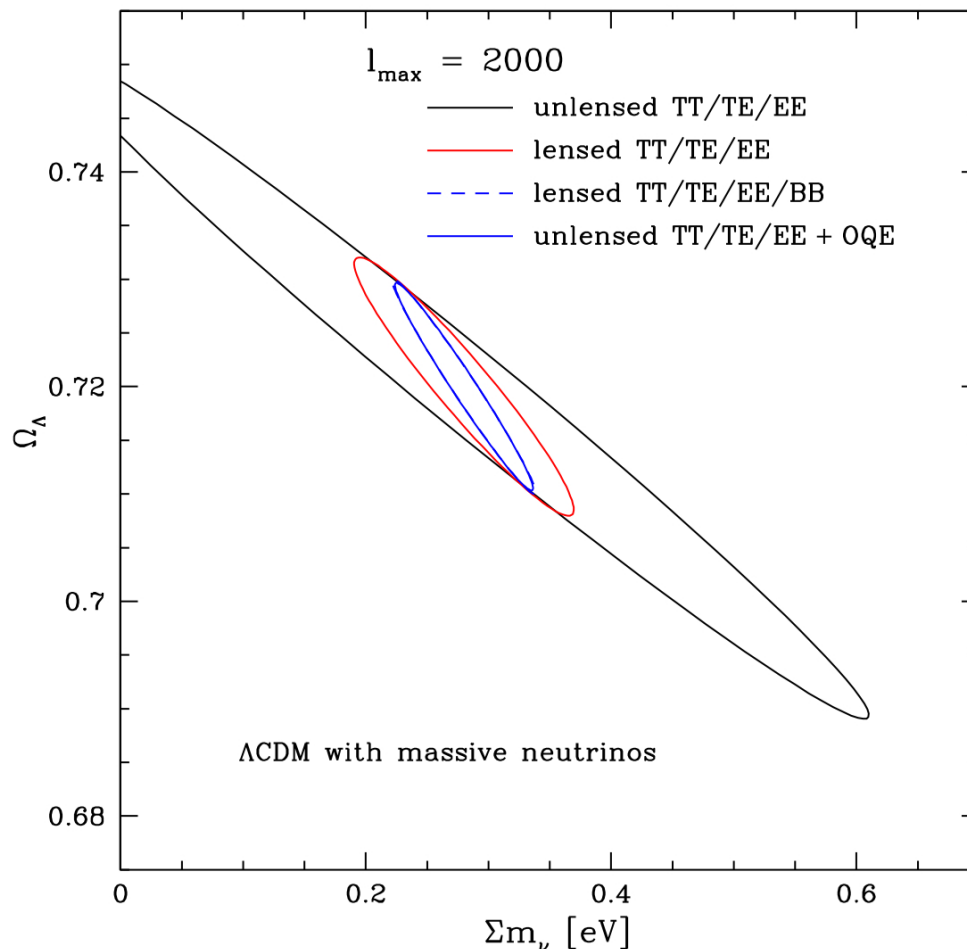
Post-recombination,
peaks \rightarrow left and adds ISW.
Pre-recombination,
peaks \rightarrow right and adds SW.

Current acceleration unique within last factor 100,000 of cosmic expansion!

CMB Lensing



CMB as a source pattern for weak lensing.
Probes $z \sim 1-5$ effects, e.g. **neutrino masses** and **early dark energy**.



de Putter, Zahn, Linder 2009

Model	Experiment	$\sigma(w_0)$	$\sigma(w_a)$	$\sigma(\Omega_e)$	$\sigma(\Sigma m_\nu)$ [eV]
Λ CDM	Planck	—	—	—	0.11
Λ CDM	CMBpol	—	—	—	0.037
w_0 - w_a	Planck+SN	0.074	0.32	—	0.13
w_0 - w_a	CMBpol+SN	0.068	0.27	—	0.044
w_0 - Ω_e	Planck+SN	0.032	—	0.0042	0.15
w_0 - Ω_e	CMBpol+SN	0.018	—	0.0020	0.050

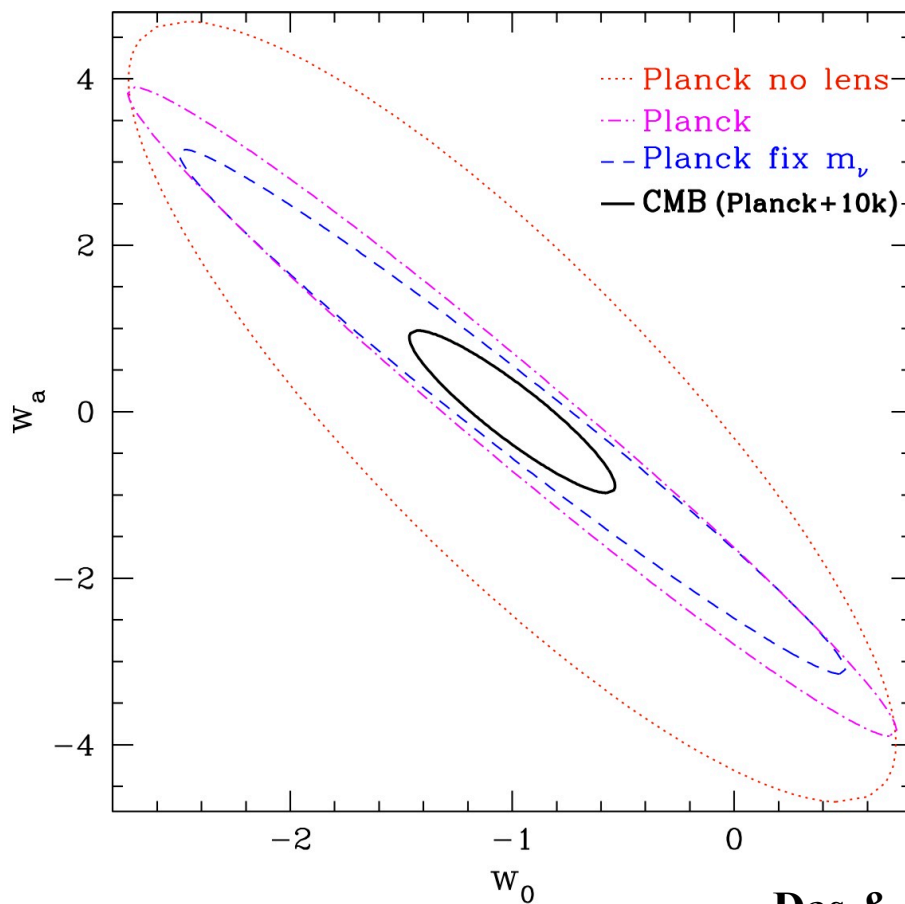
SPT/ACT gets 8/3.2 σ for Λ from CMB lensing.

van Engelen+ 2012, Sherwin+ 2011

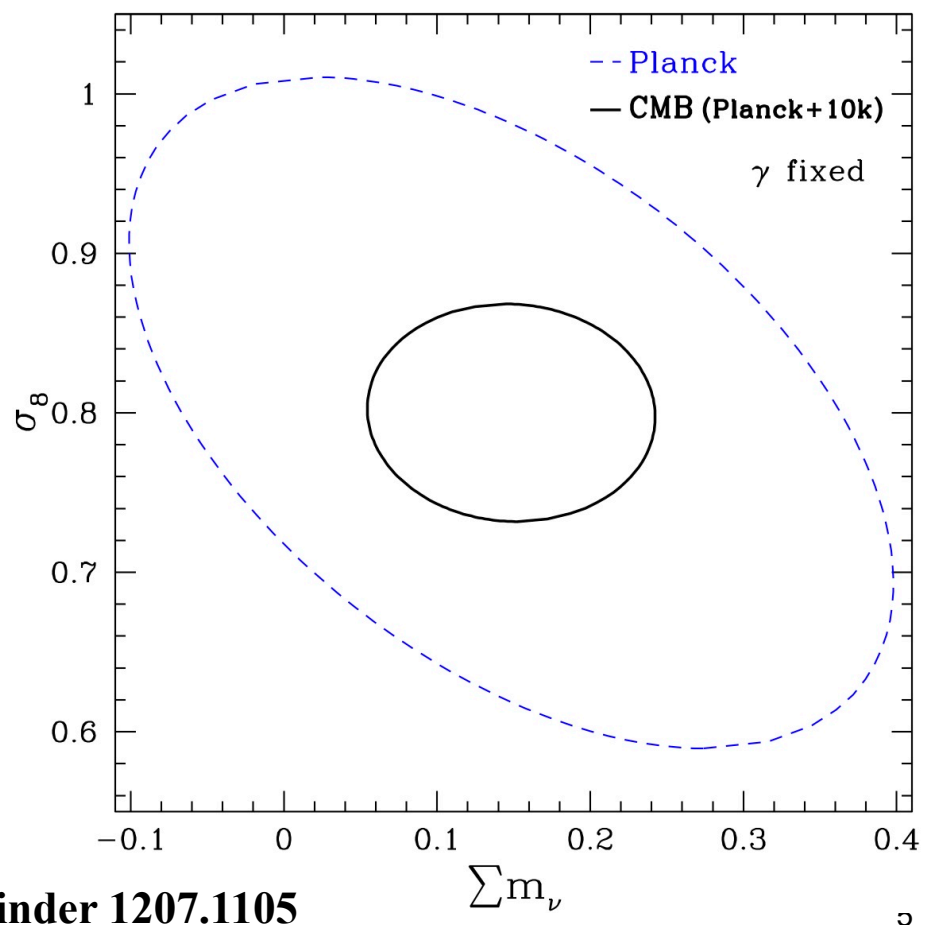
Dawn's Early Light



Ground based experiments (ACTpol, Polarbear, SPTpol) are doing CMB lensing **now**. They strongly improve Planck constraints.



Das & Linder 1207.1105



CMB Polarization



We model the next 5 years of CMB polarization lensing experiments (ACTpol, POLAR, PolarBear, SPTpol) as: **10000 deg² at 5 μ K-arcmin** (7 pol), 1' beam (insens if <4'), $I_{\text{max}}=3000$ (though 5000 pol possible).

Lensing depends on mass power spectrum so include **all effects** on it, not just vanilla Ω_m . Expand parameter space to dynamical DE, neutrino mass, gravity/growth.

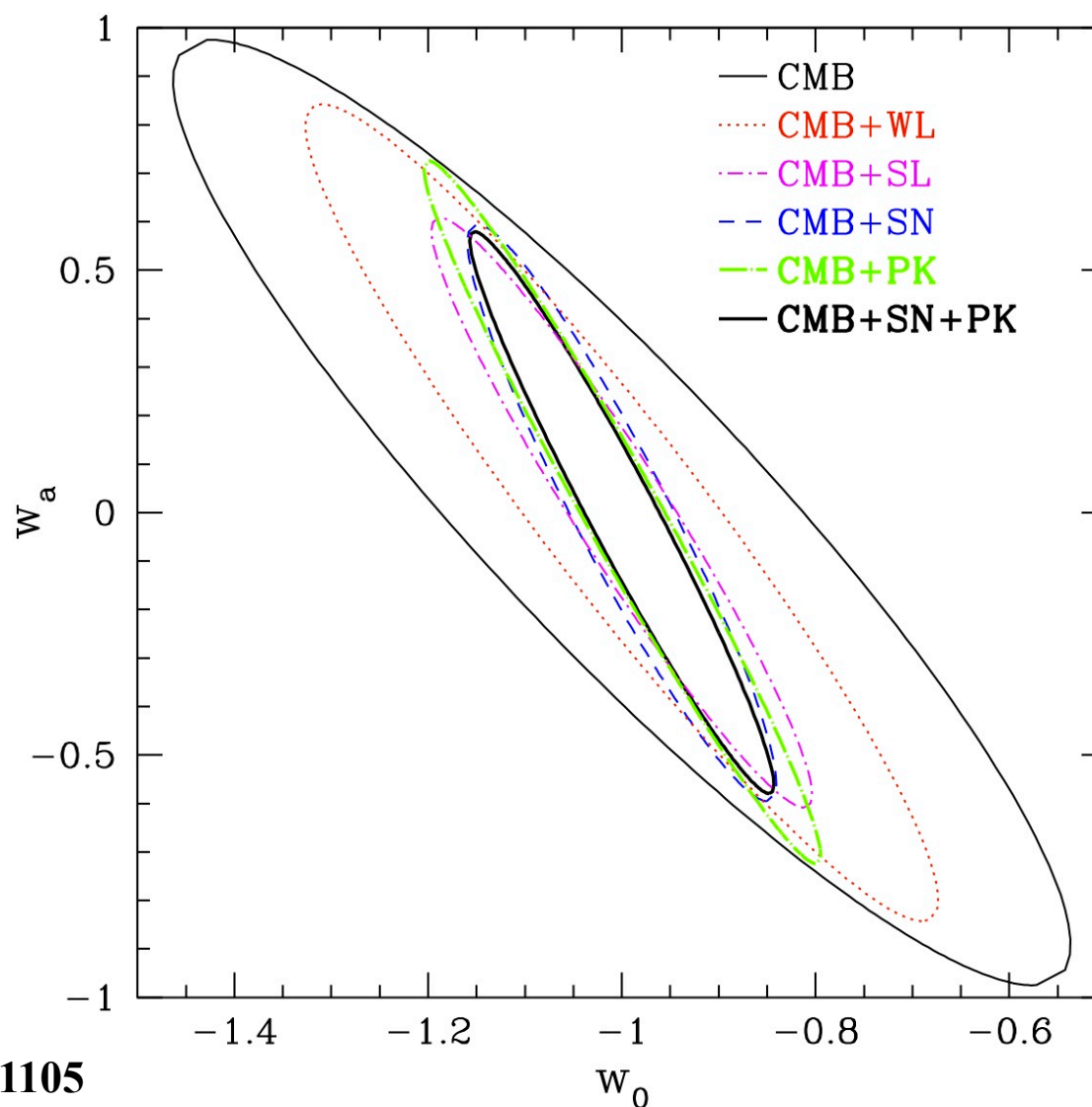
	ω_b	ω_c	ω_ν	Ω_{de}	n_s	τ	σ_8	w_0	w_a	γ
Fiducial	0.02258	0.1093	0.001596	0.734	0.963	0.086	0.8	-1	0	0.55
$\sigma(\text{Planck})$	0.000137	0.00117	0.00175	0.124	0.00337	0.00426	d	1.10	2.48	d
$\sigma(\text{Planck}+10k)$	0.0000492	0.000682	0.000666	0.042	0.00207	0.00297	d	0.305	0.642	d
Gain	2.78	1.72	2.63	2.95	1.63	1.43	d	3.61	3.86	d

Improve m_ν constraint by 2.6, DE FOM by 6.6, m_ν - σ_8 FOM (fixing GR) by 5.2.

Dawn's Early Light



This changes the DE probe landscape.



5 Year Realization



Consider **near term** (5 year), realistic landscape.

Supernovae (SN) ~ DES

Galaxy Clustering (PK) ~ BOSS

[Weak Lensing (WL) ~ DES]

[Strong Lensing (SL) ~ HST?]

SN: Linder; PK: Das, Linder; CMB: Das; WL: Das, de Putter, Linder, Nakajima; SL: Linder

Expand parameter space to all parameters affecting mass power spectrum, not just vanilla.

Dynamic dark energy: $w(z) = w_0 + w_a z / (1+z)$

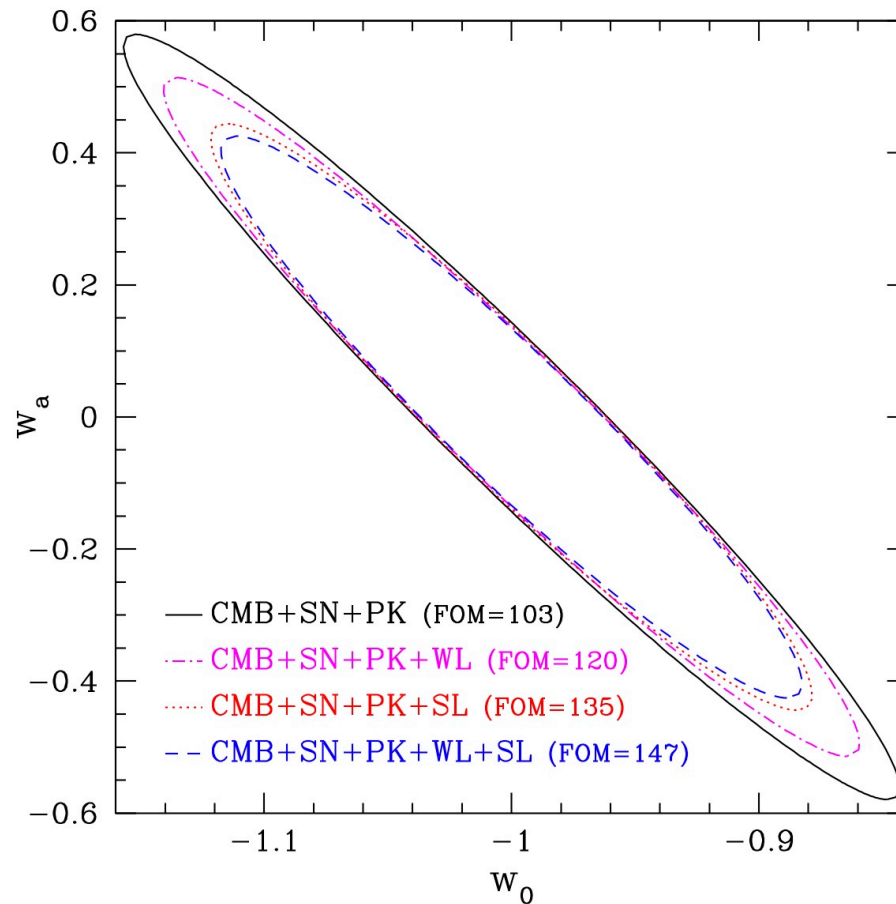
Neutrino mass: Σm_ν

Gravitational growth index (GR test): γ

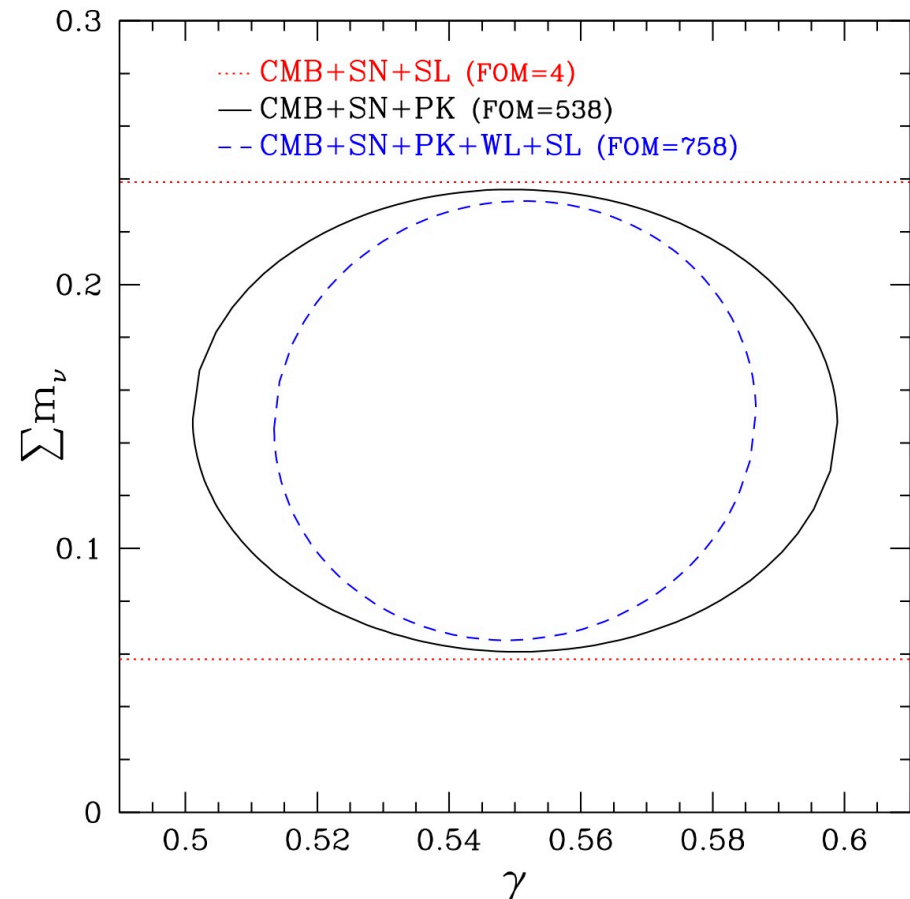
Cosmology 2017



Expansion



Growth

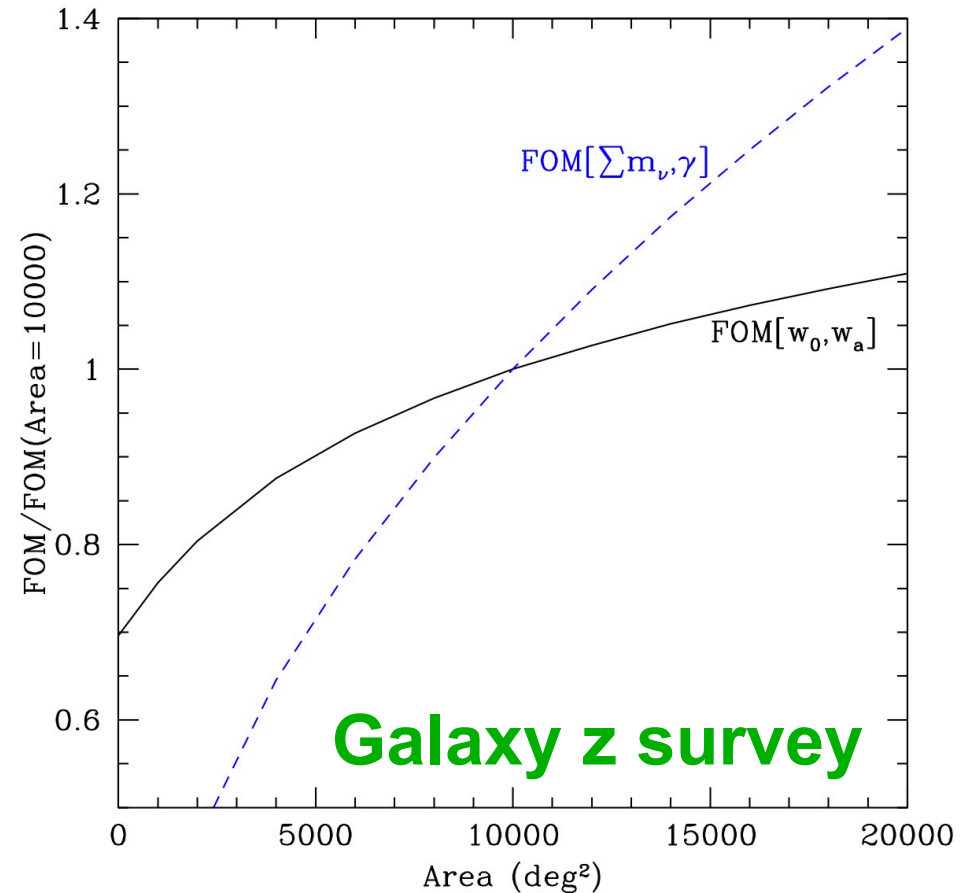
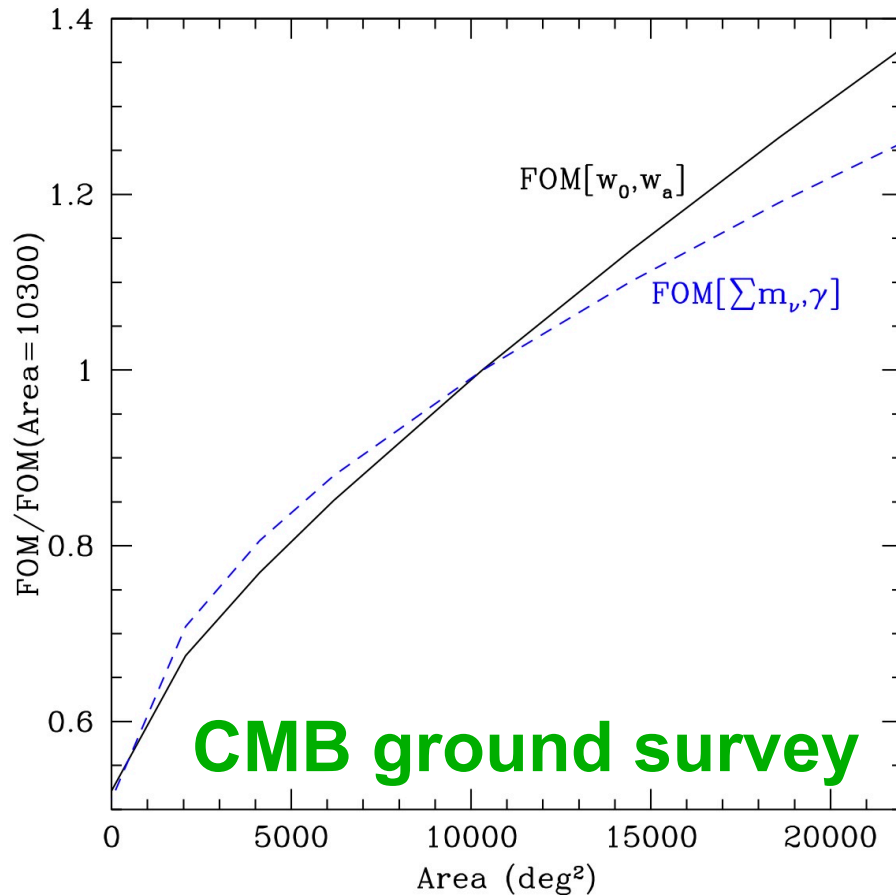


Strong program in place, but also easy to do better!

Surveys + Surveys



Very much a program: **multiple, diverse surveys.**

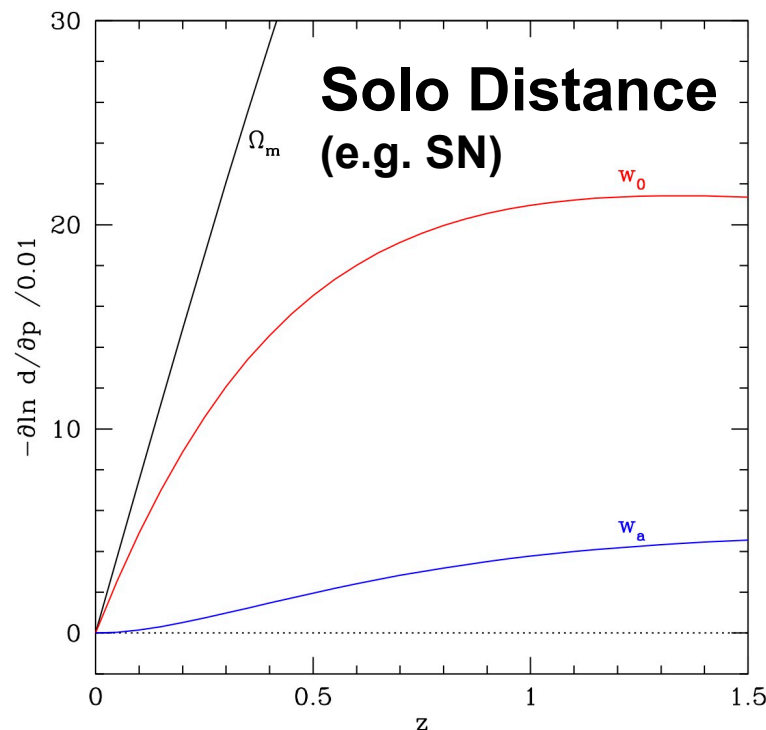


Crosscorrelations can also be powerful tool (not included).

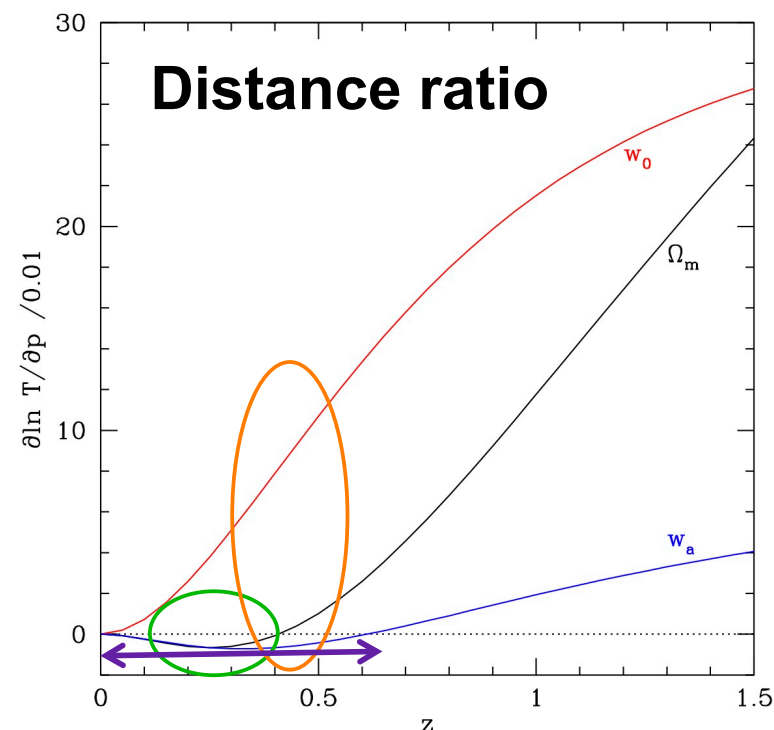
Strong Lensing Time Delays



Strong gravitational lensing creates multiple images (light paths) of a source. Time delays between paths probe geometric path difference and lensing potential. Key parameter is distance ratio $T \equiv \frac{r_l r_s}{r_{ls}}$



Sensitivity

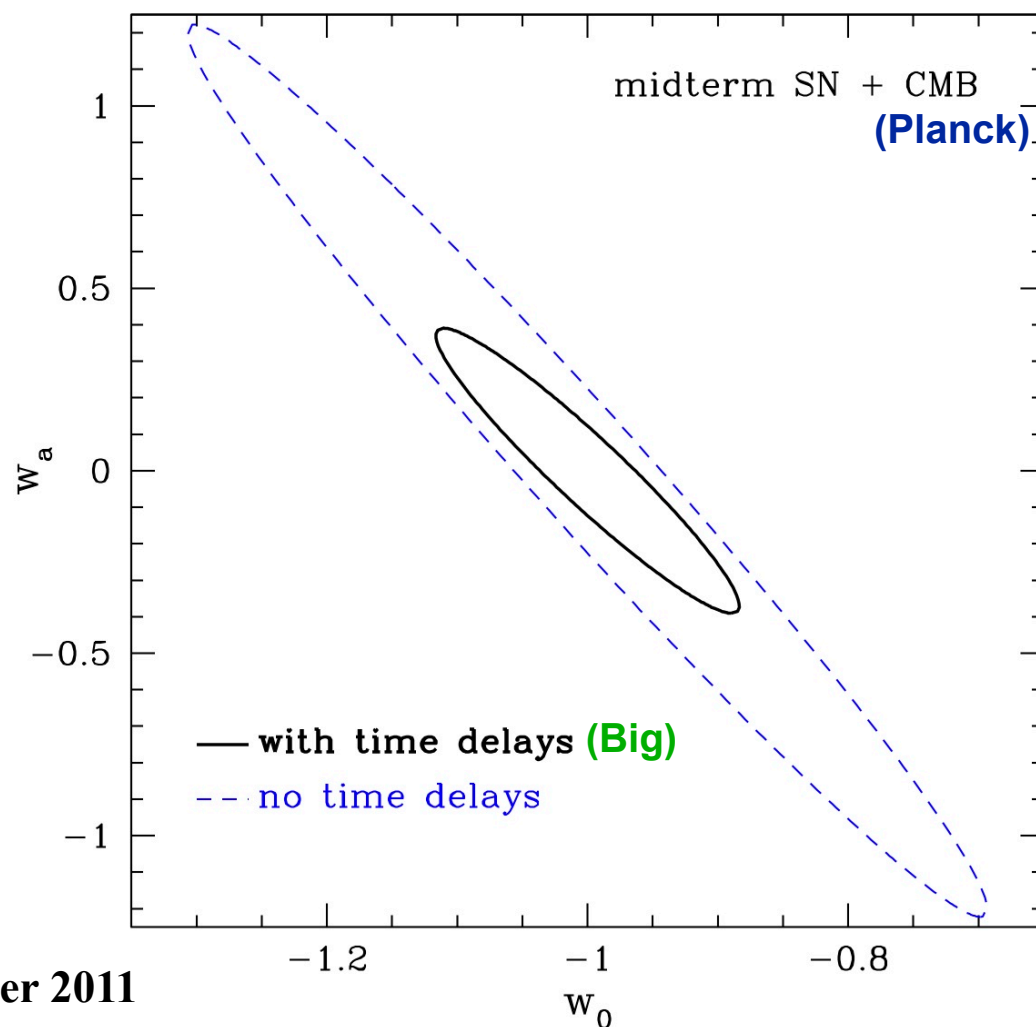


Strong complementarity first id'd by Linder 2004, first used by WMAP7 (Komatsu+ 2011), modeling advances now make it practical (Oguri 2007, Suyu+ 2010).

Time Delays + Supernovae



Lensing time delays give superb complementarity with SN distances plus CMB.



T to 1% for
z=0.1, 0.2,... 0.6

SN to 0.02(1+z)mag
for **z=0.05, 0.15... 0.95**

Factor 4.8 in area

Ω_m to 0.0044

h to 0.7%

w_0 to 0.077

w_a to 0.26

Time Delay Surveys



Best current time delays at 5% accuracy, 16 systems. 5 year aim: 38 systems, 5% accuracy = 230 orbits HST (150 gives -2%).

Need 1) high resolution imaging for lens mapping and modeling, 2) high cadence imaging, 3) spectroscopy for redshift, lens velocity dispersion, 4) wide field of view for survey.

Synergy: HST/Keck/VLT+ DES/BOSS. SN survey included. Only low redshift $z < 0.6$ needed for lenses.

Systematics control via image separations, anomalous flux ratios (probe DM substructure!). Need good mass modeling, computationally intensive.

Baseline and Enhancements



$$\text{FOM}_w = 1/\sqrt{\det \text{Cov}[w_0, w_a]} \quad \text{FOM}_v = 1/\sqrt{\det \text{Cov}[m_v, \gamma]}$$

	$10^5 \omega_b$	$10^4 \omega_c$	$10^4 \omega_v$	Ω_{de}	n_s	σ_8	w_0	w_a	γ	FOM _w	FOM _v
$\sigma(\text{CMB}+\text{SN}+\text{PK})$	4.76	6.47	6.21	0.00507	0.00200	0.0110	0.103	0.382	0.0322	103	538
$\sigma(\text{CMB}+\text{SN}+\text{PK}+\text{WL})$	4.71	5.85	5.97	0.00470	0.00192	0.00934	0.0927	0.339	0.0256	120	704
$\sigma(\text{CMB}+\text{SN}+\text{PK}+\text{SL})$	4.74	6.03	6.12	0.00414	0.00195	0.0107	0.0801	0.292	0.0319	135	551
$\sigma(\text{CMB}+\text{SN}+\text{PK}+\text{WL}+\text{SL})$	4.70	5.63	5.89	0.00403	0.00189	0.00808	0.0774	0.280	0.0241	147	758

SL program improves DE FOM by 32%.

Enhanced $z < 0.1$ SN program (150 SN \rightarrow 300, $0.021^m \rightarrow 0.008^m$) improves DE FOM by 26%.

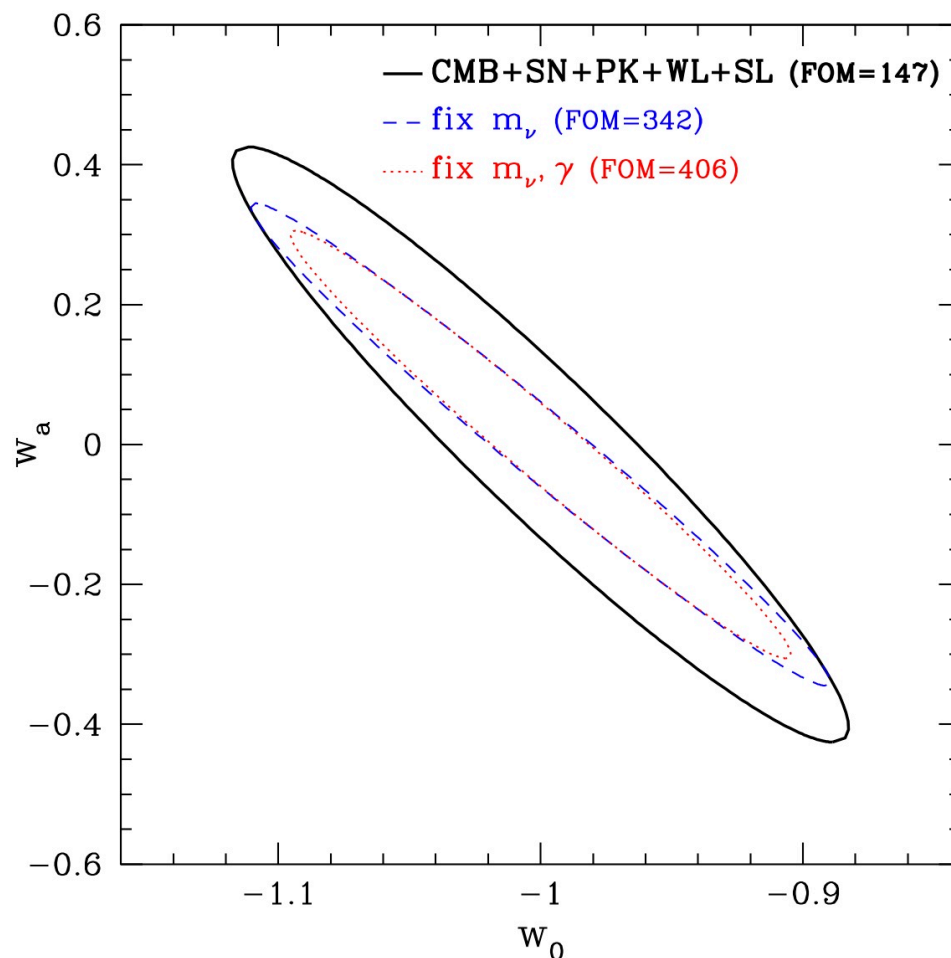
Theory/analysis: use of $l_{\text{max}} > 3000$

Theory/analysis: use of $k_{\text{max}} > 0.125 \text{ h/Mpc}$

Beyond Vanilla



Fixing parameters – DE, neutrino, gravity – opens the door to **bias**, or is simply **unrealistic** (neutrinos do have mass and we don't know how much).



Fixing m_ν makes
**FOMw 2.3x higher than
it should be.**

(And SL then very strong, +76%)
Strongest effect on w_p .

Fixing γ mostly affects σ_8 .

Fixing both implies
**CMB+surveys gives
FOMw = 406! (2.8x)**

Summary



Very much a program: multiple, diverse surveys.

Ground CMB adds +67% (FOM_w), +134% (FOM_v).

Strong program in place + easy improvements exist!

Lensing time delays improve FOM by 32%, cost 150-230 HST orbits.

Enhanced low z SN (300 with $dm=0.008$) improve FOM by 26%.

If weak lensing falters, we can still learn a lot.

Must be realistic: fixing m_v , γ projects FOM x 2.77!

Can learn $\sigma(w_a)=0.25$, $\sigma(m_v)=0.055$ eV by 2017.